ISOTOPICALLY ENRICHED PIEZOELECTRIC DEVICES AND METHOD FOR MAKING THE SAME

CROSS REFERENCE TO RELATED APPLICATIONS

[1] This application claims priority to US provisional application, serial no. 60/430,171 filed on December 2, 2002 which is hereby incorporated by reference.

BACKGROUND OF THE INVENTION

1. FIELD OF THE INVENTION

[2] The present invention relates generally to piezoelectric devices and, more particularly, to piezoelectric devices made from isotopically enriched piezoelectric materials, and methods for making the same, having improved thermal conductivity, frequency stability and phase noise qualities over currently used piezoelectric materials of natural isotopic composition.

2. DESCRIPTION OF THE RELATED ART

[3] In 1880, brothers Pierre and Jacques Curie discovered and developed the phenomenon of piezoelectricity. Piezoelectricity is the physical property where certain materials, among them crystal quartz, can be made to mechanically change their shape by applying an electric field thereto and the reciprocal phenomenon that by mechanically flexing or vibrating the crystal, the crystal generates an electric field. Over time others discovered that distinct and stable frequencies under electrical excitation can be generated by varying the

crystal directions and orientations to the crystal axis, as well as the mechanical dimensions of the crystal.

[4] During World War II, Pahl, Nacken, Spangenberg, Joos, Gunther, and Chytrek in Germany developed a process for growing synthetic quartz crystals using a hydrothermal growth technique. In the 1950s, Bell Laboratories implemented this technique on an industrial scale. Since that time, essentially all commercially utilized quartz crystals have been grown synthetically by this hydrothermal method. Other piezoelectric materials are grown synthetically using similar methods.

[5] It is well known that the use of synthetic quartz crystals of natural isotopic composition as resonators in electronic clock (square-wave) and electronic oscillator (sine-wave) circuits is limited by the crystal's inherently low short and long term frequency stability, low power handling capability, and high phase noise. Similar limitations affect the application of other piezoelectric materials. Typically, these limitations are attributed to the low thermal conductivity of the piezoelectric materials and phonon scattering naturally occurring therein. The phonon scattering, which occurs in crystal quartz of natural isotopic composition, for example, further reduces the thermal conductivity thereof as well as the Quality Factor (Q) - an important parameter affecting the frequency and phase stability of clocks and oscillators. Due to these limitations, external temperature stabilization circuitry is required to accompany the quartz and, in most instances, has limited the use of quartz crystals to only very low power applications.

[6] Typically, synthetic quartz is a compound made up of two elements, silicon and oxygen. Naturally occurring silicon is composed of three isotopes, Si28, Si29, and Si30, in the following proportions: 92.4% Si28, 4.6% Si29, and 3% S130. Naturally occurring oxygen is composed of three isotopes as well, O16, O17, and O18, with natural abundances ofin the following proportions: 99.76%, 0.04% and 0.2%, respectively.

[7] Frederick Soddy first discovered and coined the term "isotopes" shortly before World War I. Since its discovery, substantial research has occurred to develop means for isolating isotopically enriched materials. During the 1920s and 1930s, developers used mass spectrometers to separate small quantities of isotopically enriched materials from materials having isotopic levels occurring naturally. Bulk separation of isotopically enriched materials was first performed on Uranium 235 (U235) for the Manhattan Project during World War II. The bulk separation techniques used for Little Boy (first atomic bomb) included electromagnetic separation technique (calutrons) assisted by the liquid thermal diffusion technique (also known as the Clusius-Dickel method which was modified by Philip Abelson).

[8] The cost of these early techniques for stable (non-radioactive) isotope enriched materials was not subsidized by the United States government, so the customers for stable isotopes were charged full price, several million dollars per gram being standard. As a result of this high cost of separation, isotopically enriched materials had limited application.

[9] It was not until the fall of the Berlin Wall in 1991 and the collapse of the USSR that the United States had

access to stable isotopes at reasonable prices upon the development of separation methods combining gas centrifuge and laser isotope separation techniques. The buildup of commercial isotope separation facilities both in the United States and Europe in preparation for an assumed large increase in nuclear power plant construction (which never materialized) resulted in a large amount of excess isotope separation capacity which was not being used. The United States government was for many years the main supplier of all isotopically enriched materials out of the Oak Ridge National Laboratory facility, which for stable or radioactive isotopes other than U238 enriched in U235, would cost approximately $1,000 per milligram. The unused capacity of the commercial facilities has made it possible to get isotopically enriched material for as little as $50 per gram.

[10] However, it took almost a decade for the condensed matter physics community to take advantage of this now readily accessible material, so only sporadic experimentation has been done to characterize isotopic effects in single crystals of enriched elements. Further, the United States and European high-tech industries seem to be wholly unaware of this change in the price structure, so little commercialization of stable isotopically enriched materials in this field has resulted to date.

[11] The three isotopically enriched materials that have received the bulk of the experimental work are diamond (single crystal cubic carbon), single crystal germanium and single crystal silicon. Limited testing of bulk samples of isotopically enriched materials has

demonstrated great improvements in the physical properties of these elemental single crystals. Recently, the new superconductor MgB_2 has shown marked improvements in its transition temperature when made from isotopically enriched constituents.

[12] Isonics Corporation has done extensive characterization of isotopically enriched materials, both stable and radioactive, including silicon, which exhibited substantial improvements in thermal conductivity, carrier mobility and drift velocities for semiconductor applications compared to natural isotopic composition silicon single crystals. Similar improvements have been seen in isotopically enriched diamond and germanium.

[13] The most dramatic improvements in material properties have been in the measurements of thermal conductivity. According to the accepted Debye theory of heat transfer, lattice vibrations (carried by high frequency phonons) cause the transfer of thermal energy through a crystalline solid. These lattice vibrations are of very high frequencies, comparable to the electromagnetic frequencies of radiant heat. The use of isotopically enriched materials were found to increase the thermal conductivity of a material by anywhere from a factor of 1.5 near room temperature in some materials to a factor of 20 at cryogenic temperatures. This increase has been attributed to a reduction in phonon scattering caused by the isotopically enriched elements. The quantum mechanics of macroscopic systems has been applied most frequently to semiconductors, but has only been applied to piezoelectric devices as regards thermoconductivity but not to explain piezoelectric effect, until this invention.

[14] In light of the limitations of current synthetic piezoelectric materials, including quartz crystals, as discussed above, limitations which have existed for decades and were presumed to be inherent in the use of these materials in piezoelectric applications, it would be desirable to develop quartz crystals and other piezoelectric materials having substantially increased short and long term frequency stability, increased power handling capability, and decreased phase noise. Accordingly, the present invention uses the teachings from the recently unrelated fields of quantum mechanics and piezoelectrics in limiting the phonon scattering and increasing thermal conductivity through the use of isotopically enriched materials in the manufacture of synthetic piezoelectric materials and devices using the same.

[15] The present invention in its various preferred embodiments described herein provides numerous improvements and benefits over the prior art piezoelectric devices and methods.

SUMMARY OF THE INVENTION

[16] Accordingly, in at least one preferred embodiment, the present invention provides a device comprising an isotopically enriched piezoelectric material which may include isotopically enriched silicon dioxide, zinc oxide, titanium dioxide, lithium niobate, lithium tantalate, langasite, langatate, or lead-zirconate-titanate (PZT). Preferably, the lightest isotope of the material is the one enriched to provide the most improvement in piezoelectric properties including improved thermal conductivity, frequency stability and

phase noise qualities. The isotopically enriched material for use in the present invention may also consist of a single crystal.

[17] In an additional preferred embodiment, the present invention provides a method for producing single crystals of an isotopically enriched piezoelectric material comprising the steps of obtaining the isotopically enriched material in powder form, converting the isotopically enriched piezoelectric material powder into dendrite crystals by means of a first hydrothermal process; and producing a single crystal from the dendrite crystals by means of a second hydrothermal process.

[18] By using isotopically enriched piezoelectric materials, devices of greatly improved performance can be realized. New applications for such isotopically enriched piezoelectric materials of the present invention include: closer spacing of communications channels in radio-frequency equipment; lower insertion loss and higher power handling capability of discrete and surface acoustic wave crystal filters; improved frequency and phase stability in less demanding applications without the need for temperature stabilization; replacement of portable atomic clocks with quartz resonators of equal performance at a fraction of the size and cost; the ability to build compact, high powered, ultrasonic transducers in the MHz range for watercraft wake elimination, material inspection, medical diagnostic imaging, non-invasive surgical procedures and non-linear response ultrasonic beam speaker systems; high powered acousto-optic modulators, and other applications where the isotopically enriched material will result in

improved frequency, phase stability and power stability/power handling characteristics.

[19] Other and further features and advantages of the invention will appear more fully from the following detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

[20] For the present invention to be clearly understood and readily practiced, the present invention will be described in conjunction with the following figures, wherein like reference characters designate the same or similar elements, which figures are incorporated into and constitute a part of the specification, wherein:

[21] **FIG. 1** is a graph of the Value of Q versus frequency which shows the improved Q Value of the isotopically enriched piezoelectric materials and devices of the present invention;

[22] **FIG. 2** is a graph of frequency stability versus time which shows the improved frequency stability of the isotopically enriched piezoelectric materials and devices of the present invention;

[23] **FIG. 3** is a graph of carrier phase noise versus offset from the carrier which shows the reduced phase noise produced by the isotopically enriched piezoelectric materials and devices of the present invention;

[24] **FIG. 4** is a circuit diagram for clock and oscillator circuits in series and parallel which utilize isotopically enriched piezoelectric materials in accordance with the present invention;

[25] **FIG. 5** is a schematic view of a mounted crystal quartz resonator utilizing an isotopically enriched piezoelectric material in accordance with the present invention;

[26] **FIG. 6** is a partial schematic drawing of a transverse type surface acoustic wave filter comprising an isotopically enriched piezoelectric material in accordance with the present invention;

[27] **FIG. 7** is a schematic view of a device having a transducer comprising an isotopically enriched piezoelectric material in accordance with the present invention for performing non-invasive acoustic detection of tumors and acoustic surgery;

[28] **FIG. 8** is a circuit diagram for a phase comparison monopulse radar comprising a low phase noise reference oscillator having a resonator made from an isotopically enriched piezoelectric material in accordance with the present invention;

[29] **FIG. 9** is a cross-sectional view of a transducer for an ultrasonic cleaning application made from an isotopically enriched piezoelectric material in accordance with the present invention; and

[30] **FIG. 10** is a schematic view of a resonator employing an isotopically enriched piezoelectric material in accordance with the present invention for use as a speaker or buzzer.

DETAILED DESCRIPTION OF THE INVENTION

[31] It is to be understood that the figures and descriptions of the present invention have been simplified to illustrate elements that are relevant for a clear understanding of the present invention, while eliminating, for purposes of clarity, other elements that may be well known. Those of ordinary skill in the art will recognize that other elements are desirable and/or required in order to implement the present invention. However, because such elements are well known in the art, and because they do not facilitate a better understanding of the present invention, a discussion of such elements is not provided herein. The detailed description of the present invention and the preferred embodiment(s) thereof are set forth in detail below with reference to the attached drawings.

[32] A preferred application of the present invention relates to the use of isotopically enriched silicon in silicon compounds, specifically single crystal silicon dioxide (often referred to as single crystal quartz, or just quartz). Using isotopically enriched elements rather than the naturally occurring isotopic composition in silicon dioxide (three silicon isotopes and, three oxygen isotopes), reduces phonon scattering resulting in improved thermal conductivity, and more importantly improved frequency stability and reduced phase noise in piezoelectric applications, including without limitation quartz clocks and oscillator circuits. With improved thermal conductivity, accompanying external temperature stabilization circuitry is no longer required and, in most instances, the quartz can now be applied to higher

power applications, to which it was not suitable heretofore.

[33] Preferably, isotopically enriched silicon, specifically 14 silicon 28 ($_{14}Si^{28}$, usually abbreviated Si28) is used in the production of the synthetic crystal of the present invention. This isotopically enriched element greatly reduces phonon scattering (caused by dislocation from different sized atoms in the crystal's lattice) within the crystal at and below room temperature compared to naturally occurring silicon, which is composed of the three isotopes $_{14}Si^{28}$, $_{14}Si^{29}$ and $_{14}Si^{30}$ (usually abbreviated Si28, Si29, and Si30). The greatest improvement in material properties occurs when the isotope that is enriched is the lightest one, in this case Si28. The reduced phonon scattering translates directly into improved thermal conductivity, anywhere from a factor of three near room temperature to a factor of seven at reduced temperatures, and further results in reduced damping in the crystal, raising the quartz crystal's Q from 20 million to 40 million at 1MHz, and therefore increases its frequency stability by roughly a factor of 10. Additionally, the reduced phonon scattering results in a much sharper optical spectra compared to the multi-isotopic material generally available, as well as improving phase stability by -20 dBc/Hz at 100 Hz offset from the carrier and -10 dBc at 1 through 10 kHz offset from the carrier. Finally, the increased thermal conductivity decreases warm-up time, and improves power-handling capability in power transducer applications like acoustic surgery, filters and ship wake reduction.

[34] Preferably, the silicon isotope is enriched to at least 99% of the silicon component of the silicon dioxide of this application. It is important to note that the level of enrichment of any isotope will increase exponentially the expense of the enriched material; therefore, the level of enrichment should be commensurate with the level of improvement desired in the piezoelectric device.

[35] Preferably, this preferred application of the present invention also comprises the use of isotopically enriched 8oxygen16 ($_8O^{16}$ often abbreviated O16), to form isotopically enriched silicon dioxide. Again, this is the lightest of the isotopes in naturally occurring oxygen, and therefore should produce the best results. Furthermore, it is important to note that although preferred, it is not crucial to use isotopically enriched oxygen to achieve generally desirable results in light of the fact that 99.76% of naturally occurring oxygen comprises the isotope O16 and therefore enrichment thereof while beneficial would have less dramatic of an effect than the enrichment of the silicon.

[36] In this application, the isotopically enriched silicon dioxide, created from isotopically enriched silicon and natural or isotopically enriched oxygen, is then used for the hydrothermal growth of isotopically enriched, synthetic, single crystal quartz.

[37] The preferred method of manufacturing isotopically enriched cultured quartz crystals does not vary from the manufacture of traditional synthetic quartz crystals. The isotopically enriched silicon dioxide is merely substituted for the silicon dioxide at natural levels in

the manufacture of the crystals. Preferably in the form of a very fine quartz powder, the isotopically enriched silicon dioxide is first converted into a large number of small dendrite crystals, then into a much larger single crystal both by means of the hydrothermal growth technique first developed by the Bell Laboratories. The crystal's main axes are then determined by x-ray diffraction (crystallography), and the crystal is sliced, ground, polished and etched using traditional techniques into what are known in the industry as SC cut slabs. The crystal is finally mounted in a vacuum-sealed low loss mounting that is industry standard for SC cut crystals.

[38] The use of isotopically enriched materials provides for piezoelectric devices of greatly improved performance. New applications for such isotopically enriched piezoelectric materials of the present invention include: closer spacing of communications channels in radio-frequency equipment; lower insertion loss and higher power handling capability of discrete and surface acoustic wave crystal filters; improved frequency and phase stability in less demanding applications without the need for temperature stabilization; replacement of portable atomic clocks with quartz resonators of equal performance; the ability to build compact, high powered, ultrasonic transducers in the MHz range for watercraft wake elimination, material inspection, medical diagnostic imaging and non-invasive surgical procedures; high powered acousto-optic modulators, and other applications where the isotopically enriched material will result in improved frequency, and phase and power stability/power handling characteristics.

[39] **FIG. 1** is a graph of the value of Q versus frequency which shows the improved Q value of the isotopically enriched piezoelectric materials and devices of the present invention. Specifically, **FIG. 1** illustrates the accepted theoretical and practical performance of natural and synthetic quartz resonators made from quartz of natural isotopic composition with respect to electromechanical Q. The solid **Line A-A** on **FIG. 1** represents the theoretical limit of Q when resonators are made from isotopically enriched quartz comprising at least 99.9% Si28 and 99.9% 016. The dashed **Line B-B** on **FIG. 1** represents the theoretical Q versus frequency, while the solid curved lines represent measured values of Q.

[40] **FIG. 2** is a graph of frequency stability versus time which shows the improved frequency stability of the isotopically enriched piezoelectric materials and devices of the present invention. In particular, **FIG. 2** illustrates short and long term frequency stability of quartz resonators made from quartz of natural isotopic composition in comparison with two types of atomic clocks, cesium and rubidium atomic clocks. The shaded areas represent the performance of quartz, rubidium and cesium, respectively. The solid **Line A-A** represents the theoretical limits in improvements to both the short and long term frequency stability in electronic clocks comprising resonators made from isotopically enriched quartz of at least 99.9% Si28 and 99.9% 016.

[41] **FIG. 3** is a graph of carrier phase noise versus offset from the carrier which shows the reduced phase noise produced by the isotopically enriched piezoelectric materials and devices of the present invention.

Specifically, **FIG. 3** illustrates a more subtle electrical property of quartz resonators, namely phase stability, also called phase noise. Phase stability differs from frequency stability, in that it is more of a short-term stability parameter (time span of seconds) rather than a long term (minutes to hours to days).

[42] Phase stability is important in two specific electronic applications: radar systems and communications systems. In radar systems, the ability of a radar system to detect moving airborne targets and reject reflections from ground clutter, is highly dependent on the phase stability of the oscillator, which generates the radiated signal in the radar transmitter and the phase reference signal in the radar receiver. In communications systems, particularly when phase modulation is used, the number of phases (anywhere from 2 to 128 phases are presently used for phase shift modulated communications systems) that can be accommodated within a certain U.S. government allocated band of frequency spectrum is dependent on the phase stability of the phase modulator, which is in turn dependent on the phase stability of the oscillator used as the phase reference.

[43] The bottom **Curve A-A** in **FIG. 3** represents the expected improvement by using isotopically enriched quartz resonators containing at least 99.9% Si28 and 99.9% O16. The middle **Curve B-B** represents the very best performance obtained from quartz resonators of natural isotopic composition. The upper dashed **Curve C-C** in **FIG. 3** represents the minimum acceptable phase noise or phase stability performance in modern radar systems.

[44] **FIG. 4** is a circuit diagram for clock and oscillator circuits in series and parallel which utilize isotopically enriched piezoelectric materials in accordance with the present invention. Specifically, **FIG. 4** illustrates typical clock and oscillator circuits **10** and **12** which operate in series and parallel, respectively, wherein the substitution of isotopically enriched quartz as the frequency determining element in the quartz crystal resonator (Y_1)**14** results in reduced phase and amplitude noise. In addition to the quartz crystal resonator **14**, the circuits **10**, **12** comprise resistors **11**, inverting amplifiers **13**, capacitors **15** and ground connections **16**. The circuits **10**, **12** also typically comprise power lines which have been omitted for clarity. The clock or oscillator signal output (also not shown) would typically emanate from one of the inverted amplifiers **13**.

[45] Referring to **FIG. 4**, the use of isotopically enriched quartz enhances the performance of the quartz clock circuits to equal that of modern portable atomic clocks. Isotopically enriched quartz clocks, however, are advantageous in that they are approximately 1,000 times less expensive and many times smaller than current atomic clocks.

[46] **FIG. 5** is a schematic view of a mounted crystal quartz resonator utilizing an isotopically enriched piezoelectric material in accordance with the present invention. The quartz crystal resonator **14** of the present invention, as shown in **FIG. 5**, comprises a disk **30** made from a single crystal of isotopically enriched quartz containing at least 99.9% Si28 and 99.9% O16. Circular electrodes **31**, preferably comprising gold or

aluminum, are deposited on both sides of the disk **30**. Electrical and mechanical mounting pads **32** are also disposed on both sides of the disk **30**. Wires **33** act as mechanical mounts and electrical connectors leading to electrical output pins **34**. The pins **34** are mounted in a header **35** with an isolating glass **36** having the same coefficient of thermal expansion as header **35**. Preferably, the resonator **14** is hermetically sealed in a metal casing (not shown), in which a vacuum is often formed to improve performance further, as is well known in the art.

[47] **FIG. 6** is a partial schematic drawing of a transverse type surface acoustic wave filter comprising an isotopically enriched piezoelectric material in accordance with the present invention. In particular, **FIG. 6** shows a transverse type surface acoustic wave filter/resonator **20** comprising a substrate **24** comprising an isotopically enriched piezoelectric material, such as isotopically enriched quartz containing at least 99.9% Si28 and 99.9% O16. The surface acoustic wave filter/resonator includes interdigital transducers **22** etched into the metal film layer **25**, usually aluminum, that has been deposited onto the substrate **24**. The individual fingers **26** of the interdigital transducers **22** can have equal lengths (as shown) or varying lengths, to vary the filter's electrical characteristics as required.

[48] The transverse type surface acoustic wave filter/resonator **20** of **FIG. 6** is a single-phase transducer also comprising resistors **27** and a sine wave generator **28**. The use of isotopically enriched piezoelectric materials according to the present

invention also applies in the construction of surface acoustic wave filter/resonators **20** employing multi-phase transducers, which have shown improved performance over single-phase types. Improved power handling, pass-band characteristic and lower transmission losses result from the use of isotopically enriched quartz in the transverse type surface acoustic wave filter/resonator according to the present invention. Although not shown, longitudinal type surface acoustic wave filters may also be made in accordance with the present invention.

[49] **FIG. 7** is a schematic view of a device having a transducer comprising an isotopically enriched piezoelectric material in accordance with the present invention for performing non-invasive acoustic detection of tumors and acoustic surgery. Referring to **FIG. 7,** a high-powered device **40** for performing non-invasive acoustic detection of tumors and acoustic surgery is shown which includes a transducer **42** defining a concave bowl **44** that is filled with a coupling medium such as water or gel **45**. The supporting structure, metal electrodes, power supply lines and power supply have not been shown for purposes of clarity.

[50] When energized, the transducer **42** produces a high-intensity ultrasound beam **43** that is passed through the coupling medium **45**. The device **40** is set up so that the acoustic energy comes to a focus at the treatment site, a tumor **46** as illustrated in **FIG. 7**, or internal bleeding to be stopped by cauterizing local blood vessels (not shown). Because the ultrasound energy is not focused on the intermediate tissue **48**, it is not damaged. The use of isotopically enriched quartz to make the transducer **42** allows for higher power levels, higher

frequency operation and higher reliability in surgical applications.

[51] Prior piezoelectric acoustic transducers have typically been made from lead-zirconate-titanate, usually referred to as PZT. Quartz of natural isotopic composition has not been used because of its inability to be driven at high power levels without breaking. PZT can be driven at high power levels but it is limited by the maximum frequency that it can be operated at, a few hundred kHz to a few MHz. Using isotopically enriched quartz in accordance with the present invention greatly improves the thermal conductivity of the transducer **42** and allows it to be driven at high enough power levels for this high power application.

[52] In addition, the maximum frequency capability of the isotopically enriched quartz is at least two orders of magnitude higher than that of PZT, which allows higher electrical to acoustic conversion efficiency, higher resolution imaging of the internal organs and more tightly focused beams to perform acoustic surgery, such as that diagrammed in **FIG. 7**. The more tightly focused ultrasonic beam **43** produced in accordance with the present invention allows less energy to be used to produce the same power density as the prior art devices that were not capable of a tight focus. Thus, the lower power requirement reduces the chances of damaging tissue **48** surrounding the targeted area **46**. The single crystal isotopically enriched quartz transducer **42** is also much more resistant to fatigue cracking than the PZT used in prior art devices. As a result, the transducer **42** has a much greater life expectancy than such prior art devices.

[53] **FIG. 8** is a circuit diagram for a phase comparison monopulse radar comprising a low phase noise reference oscillator having a resonator made from an isotopically enriched piezoelectric material in accordance with the present invention. Specifically, **FIG. 8** shows a circuit for a phase comparison monopulse radar **50** having a low phase noise reference oscillator **52** that utilizes a resonator made from isotopically enriched quartz that provides enhanced clutter rejection and improved range and Doppler capabilities. The monopulse radar **50** also comprises a transmitter **51**, a receiver **53**, a phase measuring device **55**, mixers **56** (also referred to as frequency translators), a signal summing junction **57** and antenna **58**, having quadrants **59**. The low phase noise reference oscillator **52** preferably may use one of the circuits shown in **FIG. 4** employing an isotopically enriched quartz resonator **14** as shown in **FIG. 5**.

[54] **FIG. 9** illustrates an ultrasonic cleaning application of an isotopically enriched piezoelectric device **60** according to the present invention. Referring to FIG. 9, a tank **59** normally containing cleaning solution **61** has an isotopically enriched piezoelectric transducer **60** disposed adjacent to the bottom of the tank **59** to ultrasonically agitate the solution **61**. The transducer **60** comprises hollow centered disks **62** of an isotopically enriched piezoelectric material, such as isotopically enriched quartz, disposed between an aluminum body member **63** and a steel cap member **64**. Screw **65** holds the transducer assembly together and seals the hollow, central opening **66** which holds a coupling medium **67**, typically a gel. Power lines **68** supply electricity to the transducer **62** from a power source (not shown). Prior art transducers of this type typically employed disks **62**

made from PZT. The disks **62** made from isotopically enriched quartz according to the present invention, however, provide for a longer lasting transducer and more efficient operation at higher frequencies and higher power levels for improved ultrasonic cleaning.

[55] **FIG. 10** is a schematic view of a resonator employing an isotopically enriched piezoelectric material in accordance with the present invention for use as a speaker or buzzer. In particular, a single crystal quartz resonator **70**, as shown in **FIG. 10**, may be advantageously employed in piezoelectric sound components such as speakers (including ultrasonic speakers), buzzers and transducers. While such devices are usually made from PZT or a piezoelectric plastic film, making such components from an isotopically enriched piezoelectric material, such as isotopically enriched quartz, results in smaller, more efficient, and higher frequency capable components.

[56] Such components made in accordance with the present invention can also be operated at higher power levels without being damaged due the higher thermal conductivity and high resistance to fatigue failure of the isotopically enriched material used. Even the recently introduced non-linear response ultrasonic beam speakers, which convert ultrasonic frequencies to audible frequencies by exploiting a nonlinearity in the atmosphere would be improved by employing isotopically enriched quartz transducers. As shown in **FIG. 10**, a preferred embodiment of a quartz crystal resonator **70** of the present invention for use as a speaker or buzzer comprises a disk **71** made from a single crystal of isotopically enriched quartz containing at least 99.9%

Si28 and 99.9% O16. Large circular electrodes **73**, preferably comprising gold or aluminum, are deposited on both sides of the disk **71**. Electrical wires **75** connect the resonator **70** to a power supply (not shown).

[57] While the preferred applications of the invention described the above employ isotopically enriched silicon dioxide in the manufacture of quartz crystals for use in piezoelectric devices, the same enrichment of isotopic elements used in other piezoelectric applications (such as zinc oxide, rutile (titanium dioxide), lithium niobate, lithium tantalate, langasite, langatate, and leadzirconate-titanate), will result in similar improvements of the function of those piezoelectric materials and the piezoelectric applications thereof.

[58] Although the invention has been described in terms of particular embodiments in an application, one of ordinary skill in the art, in light of the teachings herein, can generate additional embodiments and modifications without departing from the spirit of, or exceeding the scope of, the claimed invention. Accordingly, it is understood that the drawings and the descriptions herein are proffered by way of example only to facilitate comprehension of the invention and should not be construed to limit the scope thereof.